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Economic evaluation of short rotation coppice systems for energy from biomass—A review

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ABSTRACT

Since economic profitability is the most important factor for the adoption of short rotation coppice (SRC) for energy from biomass, our objective was to analyze and summarize published knowledge about the economic evaluation of SRC. Of 37 studies, 43% reported economic viability of SRC in comparison to a reference system; whereas 19% stated economic disadvantages of SRC, and 38% reported mixed results, depending on the underlying assumptions. We found a wide variety of underlying assumptions, underlying costs, process chains and methods used to evaluate SRC systems. Of the 37 studies, 8% used static approaches of capital budgeting, 84% used dynamic approaches and 8% applied approaches in which uncertainties were taken into account. Due to the long-term nature of investment in SRC, and therewith, the uncertain development of sensitive assumptions, approaches which consider uncertainties were best suited for economic evaluation. The profitability of SRC was found to be most sensitive to the price for biomass and biomass yield, but site-specific biomass data was lacking. Despite the wide variation within each cost unit, costs for land rent, harvesting, chipping, and establishment consistently made up the largest proportion of overall costs, and should therefore, be chosen carefully. We close with suggestions for improving the economic evaluation of SRC and enhancing traceability and comparability of calculations.

Contents

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1. Introduction

The worldwide energy demand is growing faster than ever before [1]. Escalating prices for fossil fuels combined with increasing environmental problems intensified by climate change have forced policy makers to introduce policies to support alternative energy sources. RES[1] such as solar, wind, or biomass are one option to counteract climate change, since they generally create lower CO_2-equivalent emi ssions and are thus considered "cleaner" than fossil fuels.

Among RES, biomass plays an especially important role. RES currently contribute 19% of the global final energy consumption, half of which is supplied by biomass [2]. The energy present in plants is naturally produced through the process of photosynthesis and stored in the biomass itself. To generate energy from other RES, such as solar, wind and water, initial technological innovation was needed. Effort is still required to develop methods to store energy produced by RES other than biomass [3]. This is different with biomass production through SRC, because production technology is known since long and the energy may be stored a long time after harvesting, particularly in woody biomass. In contrast to other RES, socio-economic and policy aspects rather than technological aspects are fundamental to increasing the supply of energy from biomass (as confirmed by [4] for the case of land use in general). The few technological aspects which need to be improved with regard to SRC cultivation are harvesting techniques [5] and optimization of use-specific logistic chains. [6], therefore, provided an overview of the economic feasibility of power generation from SRC where 12 different scenarios with varying harvesting methods, crop distributions and power plant sizes were analyzed. What is lacking, however, is a comprehensive analysis of the economic characteristics of SRC carried out from the perspective of land owners. Consequently, in order to support an increase in the supply of biomass through SRC, we will focus here on methods and underlying assumptions for economic evaluation of SRC.

Biomass – particularly woody biomass – has many advantages over other RES.

In contrast to solar and wind power, where the energy output is highly dependent on time of day and weather conditions, power output from woody biomass can be adjusted to consumer energy demand. Hence the demand for woody biomass for energy purposes is high – 1.9 bn. m^3 of the 3.5 bn. m^3 of wood harvested annually worldwide is already used to produce energy [7]. However, increasing demand for woody biomass for material use, and particularly for energetic use, has led to the exploitation of natural forest resources and a decrease in forest area worldwide [8].

One way to increase the supply of woody biomass is SRC,[2] where fast-growing tree species such as poplar (*Populus spp.*) and willow (*Salix spp.*) are planted on agricultural land, and harvested after a short rotation period for bioenergy (electricity and/or heat) or for material use. Wood chips from SRC have better fuel properties than other renewable raw materials such as miscanthus or straw [9]. When used for electricity generation, wood chips from SRC create lower CO_2 emissions than straw but slightly higher CO_2 emissions than forest residues [10]. Furthermore, SRC is more productive per area unit than natural forest in Europe and is also ecologically advantageous in comparison to more input-intensive agricultural energy crops such as corn and rape [11–13]. Further advantages and disadvantages, along with the environmental impacts of various bioenergy sources and their utilization were compared and discussed by [10,14,15].

However, the cultivated area of SRC in Europe is miniscule in comparison to the whole agricultural area [16]. Styles et al. [9] pointed out that "the main barriers to energy crop production are the high upfront establishment costs in combination with long payback periods, lack of an established biomass market [...] associated with future price uncertainties, and a lack of policy coordination among sectors". [17] also named long payback periods as an obstacle to investment in forestry. In summary, while land-use decision making is strongly influenced by economic factors [18,19], an analysis of current research paints an inconsistent picture of the economic viability of SRC.

Previous studies of the viability of SRC used different approaches to evaluating economic viability which made use of various cost assessment techniques and divergent data sets, and were based on a wide range of assumptions. As a result, the outcomes are not comparable, thus creating further challenges for policy makers, investors and farmers. To identify suitable methods for economic evaluation of SRC, [20] summarized and compared 23 studies on the economics of SRC. In their analysis, although they stressed the impact of underlying assumptions such as biomass yield and price on profitability, they did not investigate these assumptions in depth. They also did not include methods which consider uncertainty in their analysis, distinguish between different process chains for SRC production, evaluate the necessity of the inclusion of different working steps in the analysis, or give support for the choice of realistic assumptions. All of these topics will be addressed here.

Given the wide range of variability in methods used to assess the economic viability of SRC, and particularly in the basic constraints and assumptions used, the present study will review and summarize the established knowledge on the economic evaluation of SRC. The following research questions will be answered in this review-paper:

(I) Which methods of capital budgeting have been used for economic evaluation of SRC, and what are their strengths and weaknesses?
(II) Which process chains along with different working steps and associated costs and revenues can be found in economic evaluations of SRC, which of these are worth considering and which can be ignored?
(III) What other underlying assumptions have been made in economic evaluations of SRC, and do they differ in relation to the tree species being evaluated?
(IV) What are the knowledge gaps in economic evaluations of SRC, and how can the comparability of economic analyses be enhanced?

To address the above research questions, we will demonstrate, classify and discuss the methods used to evaluate the economics of SRC. In a second step we will explain, summarize and critically analyze the assumptions made that form the basis for calculation

[1] Renewable energy sources.
[2] Short rotation coppice.

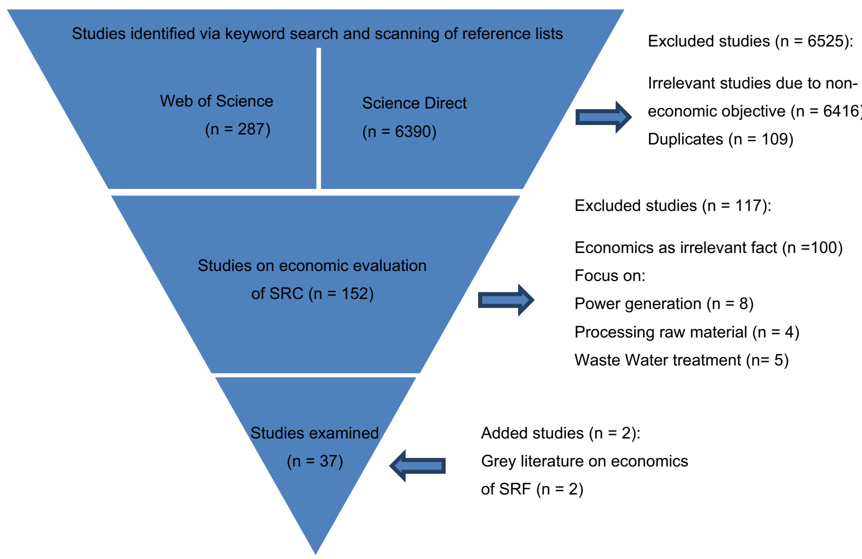

Fig. 1. Overview of literature database development. The reverse pyramid represents the three selection processes and "*n*" represents the number of studies. The horizontal arrows represent exclusion or inclusion of studies. The text next to the horizontal arrows describes the exclusion or inclusion criteria.

of profitability, including the process chain. During this step, species-specific differences in the underlying assumptions, and possible flaws in the analyses will be highlighted and discussed. Finally, we will conclude our findings and give suggestions for improvement in Sections 4 and 5.

2. Material and methods

2.1. Database creation

To identify relevant papers for this study, ISI Web of Knowledge[SM] and ScienceDirect® were queried for original studies published in peer-reviewed journals. All of the following terms were found in the literature to describe the "Short rotation coppice" concept: "*Short Rotation Coppice*" (*SRC*), "*Short Rotation Forestry*" (*SRF*), "*Short Rotation Woody Crops*" (*SRWC*) and "*Short Rotation Intensive Culture*" (*SRIC*). In our queries of the two databases, each of the following economic keywords – *investment, capital investment, capital asset, economics, profitability, economic evaluation, economic feasibility, economic uncertainty,* and *economic risk* – was combined with each of the four terms for SRC.

The total number of matches found for all possible combinations of the SRC terms and the economic keywords in each database is shown in Fig. 1. The literature was exported to the "Citavi 3.0" – Citation-Software, where duplicates ($n=109$) were automatically removed. The titles and abstracts of the remaining 6416 studies were screened to ensure suitability. Only studies which reported on the economic profitability of SRC were further investigated. The remaining 152 studies were precisely screened, and the exclusion criteria displayed in Fig. 1 were applied. Studies in which economic evaluation played a minor part and that did not provide information about the underlying assumptions used in the calculations were excluded ($n=100$). Furthermore, studies were excluded which did not allow for general comparison due to their consideration of special processes used to generate energy or fuel from the raw biomass – for example those which dealt with gasification or flash pyrolysis of SRC ($n=17$). In addition, two German studies taking uncertainties of cash flows into account and published as gray literature – one from a conference proceeding [21] and one book chapter [22] – were added to this collection. All prices were converted from other currencies into Euros using the exchange rate from March 3th 2012 according to the European Central Bank.

The majority of studies examined – 23 out of 37 – originated from Europe. Ten studies were conducted in the US, one in Canada, one in Chile, one in Benin and one in Belarus. Thirty-four studies examined only one tree species – poplar, willow, black locust, eucalyptus or daniellia. An overview of the 37 studies selected is given in Table 1.

2.2. Data collection and analysis

To evaluate methods of capital budgeting applied for economic evaluation of SRC, we sorted the selected studies based on the methods applied, and compared and discussed them. Second, we sorted the studies based upon the working steps considered. Below, we will briefly introduce each working step, and discuss them regarding their relevance for future economic evaluations of SRC. To indicate frequency of use, the number of studies which included each working step is given. Additionally we sorted the selected studies with regard to the underlying assumptions and tested for differences between analyses of different tree species. As information about underlying assumptions was not consistently provided, and due to differences in the respective process chains, the *n*[3] of data for each evaluation varied and therefore is given in the associated figures.

For an evaluation of differences among studies based upon the cultivated tree species, 35 studies based on at least one of three species – willow (*Salix ssp.*), poplar (*Populus ssp.*) and black locust (*Robinia pseudoacacia*) – were analyzed. The studies which were based only on eucalyptus (*Eucalyptus ssp.*) or *Daniellia oliveria* were excluded from this analysis, due to the small sample size ($n=1$ for each) and their evidently small importance in SRC literature. For statistical tests, *p*-values lower or equal to 0.05 were used to indicate significant difference.

3. Results and discussion

Of 37 studies, 43% reported economic viability of SRC in comparison to the reference system, whereas 19% stated economic disadvantages of SRC and 38% stated mixed results, depending on

[3] Number.

Table 1
Overview of studies examined.

No.	Methodology	Process chain	Rotation length*	Use	Interest rate [%]	Reference system	Land used	SRC species	Country/Region	References
1	DCF (NPV, IRR, BCR)	Cradle-purchaser	4	Energy	5	Energy price	sa	Willow	Finland	[9]
2	DCF (AGM)	Cradle-purchaser	3	Energy	6	Agr. crops	agr	Willow	Poland	[13]
3	DCF (NPV, Ann)	Cradle-purchaser	3	Energy	–	Agr. crops	agr & sa	Willow	UK	[21]
4	DCF (AGM)	Cradle-purchaser	3	Energy	6	Agr. crops& animal prod.	agr & sa	Willow	UK (NI)	[22]
5	DCF (AGM)	Cradle-stand	2/5	Energy	3	Agr. crops	agr	Black Locust	Southern EU	[23]
6	DCF (AGM)	Cradle-farm gate	3	Energy	5	Agr. crops& animal prod.	agr & sa	Willow	Ireland	[24]
7	DCF (NPV)	Cradle-purchaser	2	Energy	–	–	agr	Poplar	Italy	[25]
8	DCF (BEP)	Cradle-farm gate	4	Energy	7	Agr. crops	buf	Willow	Netherlands	[26]
9	DCF (NPV)	Cradle-na	4	Energy	6	Agr. crops	agr	Willow	UK	[27]
10	DCF (NPV, IRR)	Cradle-purchaser	15	Energy or fibers	4	–	–	Poplar	USA	[28]
11	DCF (NPV, IRR)	Cradle-purchaser	–	Energy or fibers	4	Coal price and fiber	agr & ero	Poplar	USA	[29]
12	CA	Cradle-purchaser	4	energy or ethanol	5	–	agr	Poplar	USA	[30]
13	DCF (NPV)	Cradle-na	–	Energy or pulp	6	–	sa	Poplar	Sweden	[31]
14	DCF (AGM)	Cradle-na	2/5/7	Energy	6	Agr. crops	agr	Poplar	France	[32]
15	DCF (NPV, BCR)	Cradle-purchaser	0.5–3.5	Energy	3	–	sa	Daniellia	Benin	[33]
16	DCF (BEP)	Cradle-farm gate	4	Energy	7	Agr. crops	buf	Willow	Netherlands	[34]
17	DCF (Annual Costs)	Cradle-purchaser	–	Energy	6	Agr. crops	agr	Willow, Polpar	EU	[35]
18	DCF (AGM)	Cradle-na	3	Energy	6	Agr. crops	min	Black Locust	Germany	[36]
19	DCF (NPV, IRR)	Cradle-purchaser	3	Energy	5	–	cae	Willow	Belarus	[37]
20	DCF (AGM)	Cradle-purchaser	4	Energy	6	Agr. crops	agr	Willow	Sweden	[38]
21	DCF (Biomass cost)	cradle-stand	5–8	Energy	5	Agr. crops	agr	Poplar	USA	[39]
22	DCF (NPV)	Cradle-farm gate	3–12	Energy	7	–	agr	Poplar	USA	[40]
23	DCF (NPV, BCR, BEP)	Cradle-farm gate	5–10	Energy	4/6/8	–	agr	Black Locust	USA	[41]
24	DCF (SEV)	Cradle-stand	–	energy	4/7/10	–	min	Eucalyptus	USA	[42]
25	ROA	Cradle-purchaser	5	Energy	3.87	–	sa	Poplar	Germany	[43]
26	DCF (NPV)	Cradle-purchaser	3	Energy	4/6/8/10	Agr. crops	agr	Willow	Wales	[44]
27	DCF (NPV,AGM)	Cradle-purchaser	3	Energy	6	Agr. crops	agr	Willow	Poland	[45]
28	DCF (NPV)	Cradle-farm gate	3	Energy	5	–	agr	Willow	UK	[46]
29	CA	Cradle-purchaser	–	Energy	6.5	–	agr	Poplar	USA	[47]
30	DCF (BCR)	Cradle-purchaser	3	Energy	5	–	agr	Poplar	Germany	[48]
31	DCF (SEV)	Cradle-purchaser	3	Energy	6	–	agr	Poplar	Canada	[49]
32	RA, DCF (NPV, Ann)	Cradle-purchaser	3	Energy	6	Agr. crops	agr	Poplar	Germany	[50]
33	DCF (IRR)	Cradle-purchaser	3	Energy	na	–	agr	Willow	USA	[51]
34	DCF (NPV)	cradle-purchaser	4	Energy	7	–	sa	Willow	Denmark	[52]
35	EUA	Cradle-na	5	Energy	4	Agr. crops	agr	Poplar	Germany	[53]
36	DCF (NPV, DCA)	Cradle-farm gate	5–16	Energy	10	Energy price	agr	Poplar, Willow	Chile	[54]
37	CA	Cradle-purchaser	–	Fibers	–	Fiber price	agr	Poplar	USA	[55]

Methodology: General remarks: DCF = Discounted Cash Flow Approach is used as an umbrella term for dynamic approaches. The target figures analyzed are given in brackets, "–" = not reported or not specified, NPV = Net Present Value, IRR = Internal Rate of Return, BCR = Benefit-Cost Ratio, AGM = Annual Gross Margin, BEP = Break-Even Point, CA = Cost Accounting, SEV = Soil Expected Value, ROA = Real Options Approach, RA = Risk Analysis, EUA = Expected Utility Approach, DCA = Discounted Cost Analysis; Process chain: cradle-purchaser = biomass is sold to any party and transport costs to this party were included, cradle-farm gate = where it was not obvious, whether biomass was to be sold or used by the SRC operator himself, cradle-stand = biomass is sold on stool, cradle-na = process chain is not described continuously; Use: energy = heat and/or power; Rotation length [years] for the second and further rotations: more than one value is given only, if no base scenario was marked; Interest rate: more than one value is given only, if no base scenario was marked; Reference system: is stated if the financial output has to compete with others than capital costs only, represented by the applied interest rate; Land used: agr = agricultural land, sa = set-aside land, buf = buffer areas around nature reserves, ero = erodible land, min = post-mining land, cae = cesium contaminated land.

* Rotation lengths after first harvest (the first rotation length is often shorter than subsequent ones).

Table 2
Properties and differences of methods used for economic evaluation of SRC. The approaches are classified into the three different groups “Static methods”, “Dynamic methods” and “Methods for uncertain expections”. Sensitivity Analysis is presented seperately, since it is more common to measure the impact of uncertain expections on the outcome than taking the uncertainty for economic evaluation into account. The components which are taken into account increase from “Static methods” to “Methods for uncertain expections”.

Methods used for economic evaluation of SRF	**Components taken into account**					
	Costs	**Benefits**	**Timing of costs/benefits**	**Uncertainty of costs/benefits**	**Worth of flexibility**	**Risk attitude of the decision maker**
Static methods	**x**					
Cost analysis	x					
Cost-type accounting	x					
Dynamic methods	**x**	**x**	**x**			
Discounted cash flow approach	x	x	x			
Annuity method	x	x	x			
Annualized gross margin	x	x	x			
Internal rate of return	x	x	x			
Soil expected value approach	x	x	x			
Break even price analysis	x	x	x			
Soil expected value approach	x	x	x			
Discounted cost analysis	x	x	x			
Methods for uncertain expections	**x**	**x**	**x**	**x**		
Expected utility approach	x	x	x	x		x
Risk analysis	x	x	x	x		
Real options approach	x	x	x	x	x	x
Sensitivity Analysis	**x**	**x**	**x**			

underlying assumptions. As we found a wide variance of underlying assumptions, underlying costs, process chains and methods used to evaluate economic profitability of SRC, our aim was to analyze the 37 studies with regard to their assumptions.

3.1. Methods of capital budgeting applied in economic analyses of SRC

Numerous methods of financial budgeting exist, each of which has its own special focus and associated benefits and drawbacks. In general, these methods can be divided between those that consider uncertainty, and those which do not. Methods which exclude uncertainty can be further subdivided into *static* and *dynamic methods* – the big difference being that static methods use average costs and benefits over time, whereas dynamic methods consider the actual timing of specific costs and benefits [56]. In evaluation methods which try to take into account the uncertainty of future cost and benefits, both amount and timing of future costs and revenues are considered. In Table 2, the main methods found in our analysis are grouped according to these categories, and their most important aspects are summarized.

Static methods were the least frequently applied methods – only three studies made use of them. Because changes in costs and benefits over time affect the profitability of SRC, it is necessary to consider them in the economic assessment. This fact is of great economic importance, since SRC cultivation involves relatively high cultivation costs at the beginning of the total cultivation time, followed by a period of lower maintenance costs as well as land rent costs. The first cash inflows are not realized until after additional costs for harvesting are incurred and the product is finally sold. According to the rotation lengths in the studies reviewed, this positive influx of cash occurred at various intervals between one and 14 years, but on average every fourth year [26,57] stated that dynamic methods are appropriate for considering the intermittent cash flows of SRC, whereas if only the costs or benefits of alternative investments are to be compared, it is better to use discounted costs or benefits, such as Discounted Cost Analysis.

Dynamic methods – applied 31 times in the studies examined here – seemed to be favored for the economic evaluation of SRC, while only three methods considered uncertainty. Sensitivity Analyses – whose exceptional position within methods dealing with uncertain expectations is discussed later on – were used 20 times in combination with dynamic methods. Although the level of uncertainty about future cash flows of SRC is high, due to limited experience and data availability, methods for evaluation appropriate in situations with uncertain expectations were rarely applied. In addition to the many well-established methods listed there, the *AGM*[4] – a relatively new method which was applied – attracts attention. By use of methods such as *AGM*, as well as *EAV*[5] and *ADAGM*[6] positive and negative cash flows – fixed and variable costs – are discounted and converted to an average annual value; thus it is the same as the *Annuity* method but is listed separately, due to its frequent use in SRC literature.

NPV[7] – one target figure of *DCF*[8] approaches – allows for comparisons among alternative investments. *Annuity* – where the *NPV* is converted into a figure representing a consistent annual cash flow of an investment over its lifetime – is an appropriate method for comparison of perennial crops with annual crops. However, certain provisions must be met: (i) Both the *Annuity* of SRC and the gross margins of annual crops should include variable as well as fixed costs. (ii) If there is a rotation cycle for annual crops, the costs and benefits of all crops should be taken into account according to their proportion [58]. A frequent point of criticism of *DCF* and *Annuity* approaches is the assumption of the ideal capital market, where interest on debt is equal to credit interest. In fact, the interest rate applied has a strong impact on both the *NPV* and the annuity [59]. But in the case of SRC, it is difficult to identify an interest rate which takes into account both the value of the money and the appropriate risk premium, given the uncertainty of future cash flows – especially as there is so little quantitative data about the potential for events which can be damaging to SRC.

The main advantage of the *IRR*[9] – another discounted cash flow approach – is that this value can allegedly be compared directly to

[4] Annual(ized) Gross Margin.
[5] Equivalent Annual Value.
[6] Average Discounted Annual Gross Margin.
[7] Net Present Value.
[8] Discounted Cash Flow.
[9] Internal Rate of Return.

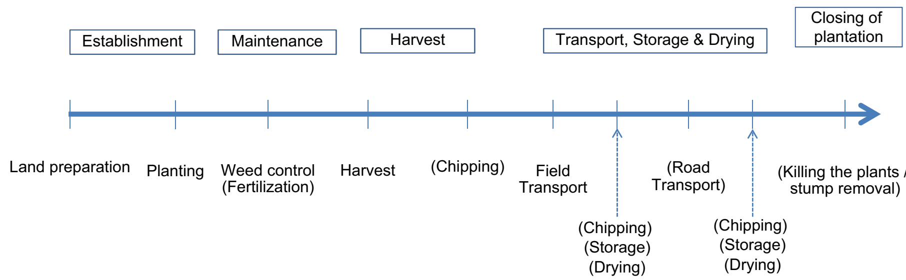

Fig. 2. Possible process chains of SRC management and individual working steps. Working steps in brackets are either optional or variable in timing. To increase traceability and comparability of studies on economic evaluation of SRC the underlying process chain along with underlying costs should be indicated in the future; since there is not only one typical process chain along with typical individual working steps but various possible combinations.

the *IRRs* of alternative investments, and to interest on credits offered by a bank. However, the underlying assumption of *IRR* – that costs and benefits are immediately invested with an interest rate according to the *IRR* – is often criticized as unrealistic. Furthermore, *IRR* is not suitable for comparisons among investments with different upfront costs, where money is invested at different points in time (i.e. in different years) and where investments have different life spans [56,60].

Due to the long life span of an investment in SRC, cash flows are subject to a high level of uncertainty. Given the high uncertainty in the profitability of SRC [46], it is surprising that only three of the 37 studies examined used methods which consider risk, such as *RA,*[10] *the EUA,*[11] *and the Real Options Approach ROA.*[12]

Risk Analysis is a tool used to quantify the risks of an investment project, and is therefore a powerful approach to evaluating investment projects under uncertainty [56]. Its drawbacks were summarized by [17] who stated, that the assumptions regarding the distributions of input data "have considerable effects on the tails of the simulated probability distribution functions" and " the correlation between different input factors are often unknown, assumed to be static or simply ignored".

In the *Expected Utility Approach* (*EUA*) the *expected value* is replaced by the *expected utility*, where the investors' attitude towards risk is also considered. EUA is a powerful way to take the investors' risk profile into account, if the investors' attitude towards risk is represented accurately by the underlying utility function. The choice of specified approaches in the expected utility framework is discussed in [17].

The Real Options Approach – a tool derived from the finance sector – is used to consider the value of flexibility, or the value of losses of flexibility. Musshoff and Jerchel [46], for example, state that the *NPV* of an investment in SRC must be 1.5 times higher, in order to account for the value of flexibility losses in land use through SRC cultivation. Critics of the approach mention that real options are not arbitrarily divisible and there is not always a market or price for real options [56].

Sensitivity Analysis is not a method which accounts for uncertainty, but rather a method to test if the uncertainty of particular input parameters had a significant influence on the outcome of the analysis [56]. In 20 out of 37 of the studies examined, *Sensitivity Analyses* were carried out to check whether the variance of input data was crucial to the predictions about the economic viability of SRC. In all cases, the authors concluded that the uncertainty of input parameters – especially biomass price and biomass yield assumptions – was crucial in evaluating the profitability of SRC. This result is an important indicator of the need for economic calculations which take heed of the uncertainty of both prices and yields for SRC.

[10] Risk Analysis.
[11] Expected Utility Approach.
[12] Real Options Approach.

3.2. Process chains and working steps

To ensure both traceability and comparability of calculations, it is very important to precisely describe the process chain used as a basis for the economic evaluation of SRC. Different working steps, along with differences in time requirements, type of machines used and the number of hours they are operated, and distances to market must all be taken into account (Fig. 2), since these lead to varying costs, and thus effects on the profitability of SRC. Due to the lack of experience with SRC management worldwide, and the manifold possibilities in terms of working steps, it is a challenge to choose appropriately among them, which ultimately affects the costs calculated and therewith the financial outcome. Therefore, we have dedicated a large section of this review to providing an overview and explanation of all possible working steps in SRC production – from cradle (land preparation and planting) to purchaser – that have the potential to contribute a meaningful share of overall costs. These include costs for: establishment, harvesting and chipping, transport loading, storage and closing of the plantation [28,33,61,62]. Maintenance costs, such as fertilization, application of insecticides, and weed control, contribute only a small share to overall costs [29,63] and therefore will not be discussed in detail in this paper. As an indicator of the necessity to include a particular working step in an economic analysis of SRC, we additionally indicate the number of studies which carried out each working step. We end with an overview of costs per working step and a summarizing definition of four typical process chains and the studies we examined which can be categorized under each.

3.2.1. Analysis of working steps

Establishment costs are one of the highest cost units of SRC cultivation [33]. Hence, careful consideration must be given to which actions must be included in analysis, and which can be omitted [9]. For successful cultivation of SRC, good site conditions are necessary [64] {Bemmann 2010 #182 hence costs for land preparation as well as costs for procurement or generation of cuttings or seedlings and for planting must be considered, as they are the basis for growth.

Among the studies analyzed, 35 *of* 37 considered costs for land preparation, cuttings and planting

Competing vegetation and therewith *weed control* are among the most important factors influencing the growth of SRC plants in the first couple of years after establishment of the plantation [48,55]. Thus, in 34 *out of* 37 studies, pre-emergence herbicides were applied either immediately before or after planting. Depending on site conditions and relative levels of competition between weeds and trees, *weed control* might be required one to three times a year in the first one or two years following plantation establishment [55,65,66]. In 29 *out of* 37 studies, costs for weed control were indicated.

Harvesting methods for SRC can be divided into two main types. First, there is a fully mechanized harvesting system, where SRC trees are harvested and chipped in one continuous operation. Second, there are harvesting techniques where harvesting, skidding and chipping of the shoots are carried out in two or more working steps. This can be accomplished either manually – with a handheld chainsaw – or with machines which harvest and collect the shoots to deposit them at a central spot where they are then dried and/or chipped. Fully mechanized harvesting systems are said to be the cheapest for short rotations of about three years due to high productivity [5,22,61]. This 3-year threshold is based on tree diameter at harvesting height. However, newer machines are capable of harvesting stems of up to 13 cm in diameter, which must be considered in future calculations. For SRC with a rotation length of ten years, the manually harvesting technique is economically competitive due to the relatively high amount of biomass per stem [61]. Since harvesting is always required, with the exception of the two studies where biomass is sold at stool, all of the studies examined indicated harvesting costs.

Costs for chipping were indicated in 23 studies. As noted, in two of the 37 studies the biomass was sold at stool, and in five, biomass was sold as round wood, thus chipping was not required. The remaining studies did not give explicit information about chipping, since the fully mechanized harvesting technique where chipping is automatically included was applied.

Field Transport refers to transport on field and dirt road, whereas *Road Transport* takes place on paved roads. Transport distances in the studies examined ranged from 5 to 65 km, with a median of 30 km. Even in countries with large land bases like the USA and Canada the average transport distance was 44.7 km, due to the strong influence of transport cost on profitability [23,28,32].

Loading stems or wood chips on a transport vehicle is always required when biomass is moved from one interim storage site to another, or to final storage. Round wood or wood chips are, for instance, stored at the field site or at the farm prior to being transported to the power plant.

Many interim storage steps imply rising costs for loading and unloading, which must be included in economic calculations. Fourteen of our studies considered field transport and 22 road transport, but only eight studies took costs for loading into account.

Two main types of woody biomass *drying* can be distinguished – passive, natural drying without any external energy input, and active drying with external energy input. Furthermore, the medium to be dried can be round wood or wood chips. Round wood is usually air-dried at the field site, where the water content is generally reduced from 50% to 25–30% in one summer [67]. Wood chips can either be air-dried, or dried with external energy input. Some of the benefits in terms of energy and cost savings gained from air-drying of wood chips are lost through decomposition [68]. Active drying, in contrast, increases energy, material and labor costs. Further details on drying technologies for bioenergy may be adopted from [69].

When biomass is provided for energetic use in heating plants, drying is not necessarily needed. For smaller, domestic heating plants, the acceptable water content of biomass can be as high as 30% [70]. Costs for drying were taken into account in only four out of the 37 studies. Hence, it seems to be generally assumed that drying of wood chips is either not done, or it is done passively without direct costs for drying. In the latter case, at least additional costs for loading and unloading the biomass at the interim storage site should be considered. Due to its higher heating value, it is obvious that biomass with a relatively low water content of about 20% can fetch a higher price [71].

At the end of the total cultivation time, the plantation must be closed – which means killing the plants and preparing stool free topsoil – if new trees are to be planted mechanically, or if farming with conventional agricultural crops is desired. Therefore, stools can be either pulled up and collected, or killed using rototillers up to a soil depth of 30 cm or by herbicides. The overall cost of this process depends primarily on the given conditions. Herbicide application is the cheapest method, at about 250 Euro per hectare, and is suitable if the land can be left fallow until the stools decompose. Pulling up and collecting the stools is the most expensive method, whereas milling or crushing the roots with rototillers is the method with the best cost-benefit ratio [62]. Fourteen out of 37 studies included costs for stool removal. However, because SRC is such a long-term project it is often not known ahead of time what the preferred land-use will be at the end of the rotation period

Additional costs that were found in some studies included costs for *Planning* ($n=1$), *Marketing* ($n=3$) *and Supervision* ($n=10$). We however, feel these costs can be ignored for small scale SRC areas, and should be included in economic calculations only if several SRC sites are to be managed simultaneously.

3.2.2. Overview: proportion of overall costs per cost unit

To highlight which cost units (costs for working steps plus costs for land rent) had the biggest impact on the overall costs, and thus should be chosen carefully in future calculations; we calculated the proportion each individual working step contributed to the overall costs per study, and summarized the results in Table 3. We included only costs which were clearly assignable to the cost units we have defined for this review.

The three cost units with the highest median share of the costs included in the studies we analyzed were land rent, harvesting and chipping, and establishment, which is in line with [23,28,61,9]. This ranking remained valid even when we analyzed the data separately according to the four process chains described in 3.2.3. Only where the biomass was considered to be sold per stool (cradle-stand process chain) did the ranking of proportional costs change – to land rent, establishment and maintenance. Thus in an economic evaluation of cradle-stand SRC production, maintenance costs have to be chosen carefully, as well. Even when more cost units were included in the calculation, the relative proportion of costs attributable to land rent, harvesting and chipping, and establishment did not change. Therewith, the overall variance of proportionate cost assumptions could not be explained by the process chain. Ericsson et al. [38] mentioned the nascent status of SRC production in most countries as one reason for heterogeneity of cost estimates. In our study, harvesting and chipping, and costs for land rent were found to have the highest variance. As harvesting and chipping can be accomplished by one of several techniques in addition to the cost differences per county this result is plausible. The high variance of

Table 3
Costs per cost unit as a proportion of overall costs found in the studies examined. On average costs for land rent, harvesting and chipping and establishment are the largest contributors to the overall costs and therefore have to be chosen carefully.

	Minimum	Maximum	Mean	Median	Number of values
Establishment	4.68	54.96	24.99	24.39	28
Maintenance	0.76	29.8	10.33	6.54	16
Harvesting and chipping	4.67	91.22	33.7	26.21	27
Field Transport	5.28	14.82	9.9	9.75	7
Road Transport	1.81	26.87	13.41	11.99	11
Loading	1.31	7.28	4.4	4.8	3
Storage	5.68	12.84	8.65	8.05	4
Marketing	5.78	9.57	7.06	5.83	3
Supervision	0.3	28.24	6.69	4.31	10
Closing	1.38	14.47	7.47	8.51	11
Land rent	1.28	63.73	33.97	37.9	16

Table 4
Overview of working steps per process chain. Working steps indicated in brackets were found in some, but not all of the studies falling in the particular category. "Cradle – stand" summarizes studies where biomass is sold at the stool. "Cradle – farm gate" summarizes studies where biomass is not delivered to any purchaser. "Cradle – purchaser" summarizes studies where the end of the process chain is either a power plant, a marketplace or a mill. "Cradle – na" represents all studies where the destination and therewith the process chain is not precisely defined. By trend the number of working steps along with the production costs increase from "Cradle – stand" to "Cradle – purchaser".

Process chain	Establishment	Maintenance	Harvest	Transport	Storage and drying	Closing of plantation
Cradle – stand (n=3)	x	x				
Cradle – farm gate (n=7)	x	x	x	Field	(x)	(x)
Cradle – purchaser (n=22)	x	x	x	x	(x)	(x)
Cradle – na (n=5)	x	x	x			

costs for land rent, stated for instance by Toivonen and Tahvanainen [23] may be due to the heterogeneity of soil quality and of regional prices for land, or alternatively, due to different definitions of land rent. As stated by Ericsson et al. [38]: "It is difficult to estimate the general cost of land, as it may be defined as a tenancy cost, the interest rate on loans taken out to purchase the land or the opportunity cost."

We found the fourth and fifth most important cost units to be road transport – with a median of 11.99% – and field transport with a median of 9.75%. As they are directly dependent on the yield level per hectare [48] and the distance to market [23]. Both factors must be included in the determination of appropriate transport costs.

We found closing of the plantation to be the sixth most important cost unit. Further cost units – listed by median impact on the overall costs – are storage, maintenance, marketing, loading, and supervision. In the future, the costs for SRC management are expected to decrease, due to the high learning potential with regard to SRC management [72]. De Wit et al. [72] indicated potential cost reductions in the management of SRC poplar in Italy of 65% and SRC willow in Sweden of 57% within the next 20 years. Therefore, more effort needs to be put into investigations of the development of SRC management costs over time, in order to include likely trends in future calculations.

3.2.3. *Process chains of the studies examined*

To summarize and simplify the classification of studies according to their underlying working steps and associated costs and revenues, we defined four process chains and assigned each of the studies we examined to one of the four (Table 4). Along the continuum from *"cradle-stand"* to *"cradle-purchaser"* methods, both costs and revenues tended to increase. Facultative, working steps that may or may not be carried out, working steps are indicated in brackets.

The majority of the studies examined used the process chain *"cradle-purchaser,"* where biomass was sold to any party and transport costs to this party were included (Table 4). Seven studies chose a *"cradle-farm gate"* process chain where it was not obvious, whether biomass was to be sold or used by the SRC operator himself. Three studies were based on the *"cradle-stand"* process chain, where biomass was sold on stool. Thus no costs for harvesting, chipping and transport were included, but the price for biomass was low compared to wood chips, at about 15€ per ton fresh matter (Fig. 3). In five studies, the working steps were not specified continuously after harvesting, but single working steps were stated *"cradle-na"*.

3.3. *Underlying assumptions of the studies reviewed*

The assumptions on which an economic calculation is based strongly affect the financial outcome. As there is little real data on costs and benefits due to the small area of SRC worldwide, we give an overview of the underlying assumptions used in the studies reviewed. We also provide the results here of statistical tests we conducted to determine whether differences in the assumptions made for different tree species were statistically significant.

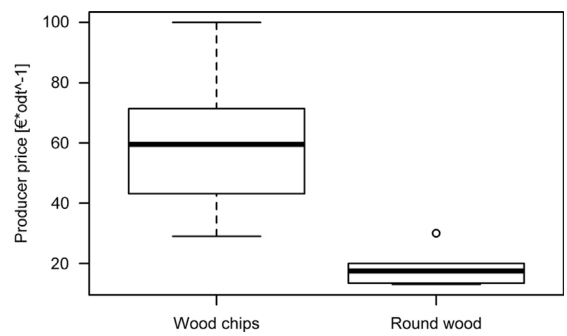

Fig. 3. Wood chip (n=25) and round wood (n=6) prices [€ odt^{-1}] of examined studies (n=25). Wood chip prices are on average 2.6 times higher than prices for non chipped wood.

3.3.1. *Returns of biomass sale*

The price for SRC biomass, round wood or wood chips, was viewed by [24,26,32,48,73] as the most important factor for the profitability of SRC. In all other studies, biomass price was considered to be one of the most important factors. Studies which directly compared SRC to agricultural crops stated that the opportunity cost of competing land uses also has a significant influence on the economic viability of SRC [22,48]. Therefore, the biomass price assumption for economic calculation of SRC must be as realistic as possible. Furthermore, it is important to highlight the measurement unit to which the price refers. All of the following measurement units were found in the studies examined: [€ GJ^{-1}], [€ MWh^{-1}], [€ odt^{-1}][13] and finally [€ t^{-1}] with accompanying information about water content. For instance, [€ GJ^{-1}] and [€ MWh^{-1}] can refer either to the energy content of biomass or to the converted energy output of biomass. In the latter case, the efficiency factor of the heating system must also be provided. A similar problem exists for [€ odt^{-1}] and [€ t^{-1}]: When the water content is known, the price for biomass can be converted to the price per odt, according to its heating value. However, there are additional costs for the dry-down of biomass to zero % water content, which are dependent on both the original water content and the technique applied.

In all studies, the prices for round wood were given for a water content of between 40% and 50%, while the prices for wood chips were given in [€ GJ^{-1}], [€ MWh^{-1}], [€ odt^{-1}] or [€ t^{-1}], which makes it difficult to compare them. To make prices for this study approximately comparable, wood chip prices were converted to prices per [odt].

Prices for round wood were ranging from 14.8€ per odt up to 31.4€ per odt with a mean price of 23.01€ per odt.

[13] Oven dry ton.

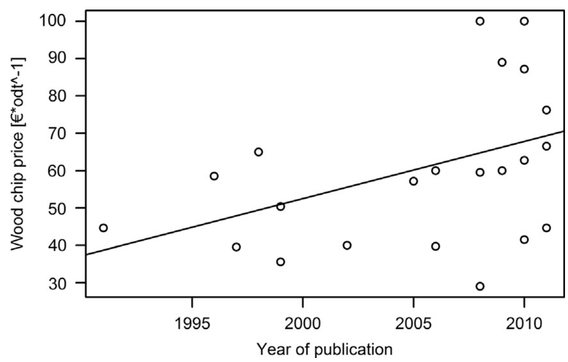

Fig. 4. Wood chip prices of the studies examined by year of publication ($n=25$). The prices for wood chips are significantly increasing over time, but absolute deviation is scattering stronger in the last years. These trends should be considered when evaluating economics of SRC.

Wood chip prices differed strongly within the studies examined (Fig. 3), ranging from 30€ per odt up to 100€ per odt with a mean price of 60.69€ per odt.

A mean price difference of 37.6€ per odt between wood chips and round wood was found in the analyzed literature (Fig. 3). Hence, chipping wood offers an additional benefit to SRC. While a trend of increasing prices over time was confirmed via regression analysis (Fig. 4), no statistically significant price difference was found between countries. The R-squared value for this regression equaled about 0.14, which means that only 14% of the total variance could be characterized by the regression line, but the increasing price over time was statistically significant.

Considering the fast growing population, the increasing demand for fossil fuel and increasing prices, this result seems to be plausible. Styles et al. [9] for example, reported that large-scale energy producers in Ireland were offering more and more money for wood chips. Rosenqvist and Dawson [26], on the other hand, referred to the opposite situation in Sweden, where prices for wood chips were decreasing due to increasing SRC area, and an associated increase in wood chip supply. However, in the long term, an undersupply of woody biomass, and therefore, increasing biomass prices seem to be more likely [74]. Nevertheless, some authors reported that there is still no established market for wood chips in their country, as indicated by the great price variance within the countries themselves (see for instance [51]). This fact, and the relatively long time span – 20 years – covered by the studies may also have contributed to the high variance of wood chip prices.

3.3.2. *Biomass yield*

The biomass yield of SRC was seen by [21,22,37,47] as the most important driving factor for the economic success of SRC. In all remaining studies in our sample, it was named as one of the most important driving factors. Thus biomass yield and price assumptions have to be made critically and as realistically as possible.

Growth of an SRC stand can be expressed in one of two ways – either by the total growth of a stand over its lifetime in relation to its area, or by the average annual growth – often referred to as MAI.[14] To calculate the MAI, the total growth of a stand is divided by the number of years since establishment or since resprout. In forestry, the measurement unit "cubic meters" for timber is most commonly used. The measurement unit for SRC yield when expressed as total growth – especially in regard to SRC timber for energetic use is "tons per hectare", and for average annual growth (MAI), "tons per hectare per year". To make biomass prices comparable in terms of their dry matter content, they are commonly given as "oven-dry tons". In *four* of 37 of the studies examined, yield was indicated as total growth. In the remaining studies, yield was given as MAI. Thirty-five of the 37 studies reported the yield in "oven-dry tons" [odt], whereas only *two* of 37 studies indicated the yield in tons, along with a statement of the water content.

Yield development over the lifetime of SRC trees was frequently discussed [33,75]. A two-sided *T*-Test of the Mean Annual Increment (MAI) in the first and subsequent rotation periods from the studies examined showed evidence of an increase in yield over time. The median MAI for the first rotation was 8 odt ha^{-1} a^{-1} and the median MAI of second and further rotations was 9 odt ha^{-1} a^{-1}, which represents an average increase of 12.5% (Fig. 5). This result concurs with the findings of [42,33] who reported an average yield increase of 11% from the first to the second rotation.

A general increase from the first to second rotation seems logical, since in the first years, cuttings use energy to establish a rooting system and must compete with weeds for light, nutrients and water.

A closer inspection of MAI and MAI development amongst the three tree species – black locust, poplar and willow – indicated no statistical evidence either for different MAIs, or for different MAI development over time (Fig. 6). The median MAI of black Locust was 5.7 odt in the first rotation and 7.35 odt in further rotations. The median MAI of poplar was higher, with 8 odt in the first rotation and 9 odt in further rotations. The median MAI of willow was the highest, with 9 odt in the first rotation and 9.5 odt in further rotations. The absence of statistically significant differences between the yields of the various tree species may be due to the fact that most of the studies examined calculated on the basis of average yields per country, which have mostly been derived from test plots. Strauss et al. [33], Buchholz and Volk [13], Avohou et al. [36], Styles et al. [9] and Ericsson et al. [24] affirmed that SRC yield strongly depends on site characteristics, in particular on water supply. If water on site is scarce, urban or industrial water – if available nearby – is a cheap and efficient way of irrigation which leads to increased yields, and therewith increased profitability of SRC [76]. Furthermore, biomass yield derived from test plots reflects yield levels under optimum conditions. So, they do not represent yield levels achievable under field conditions in every case. Krasuska and Rosenqvist [48] assumed a 25% lower yield level when taking into account losses involved with commercialized cultivation. However the fact that SRC cultivation is still in the initial phase and there is great potential for increasing future yields should be considered. De Wit et al. [72] who evaluated past trends in development of different wood productions systems and provided a future outlook for different wood production systems, stated that yield is the factor with the strongest influence on increase in the profitability of SRC. According to [72]: "Yields were augmented through implementation of improved breeds and clonal varieties, increased fertilization levels, better pest control and ongoing mechanization in planting and tillage."

3.3.3. *Total cultivation time*

Assuming an appropriate total cultivation time for SRC, the period from establishment until closing of the plantation is economically relevant, as it affects the period of discounting each cash flow. In the studies examined, total cultivation time varied between eight and 50 years (Fig. 7). The total cultivation time of black locust varied between eight and 30 years, with a median cultivation time of 15 years. Poplar was cultivated for eight to 50 years, with a median cultivation time of 21 years; and willow for 16–25 years, with a median cultivation time of 22 years. However, a Kruskal–Wallis one-way analysis of variance showed no statistically significant difference between the cultivation times of the three tree species.

[14] Mean Annual Increment.

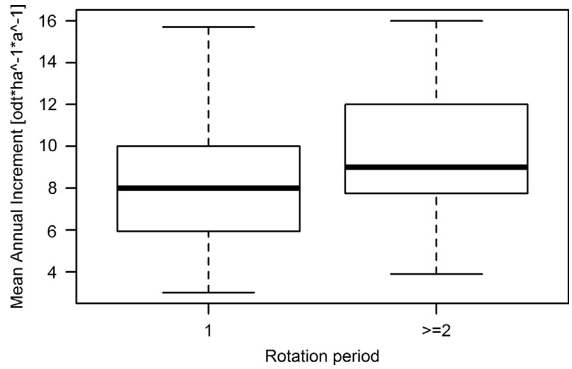

Fig. 5. MAI in the first (n=35) and second (n=35) or later rotation(s) (2+) of black locust, poplar and willow. On average the MAIs examined are increasing from the first to the second and further rotations by 12.5%.

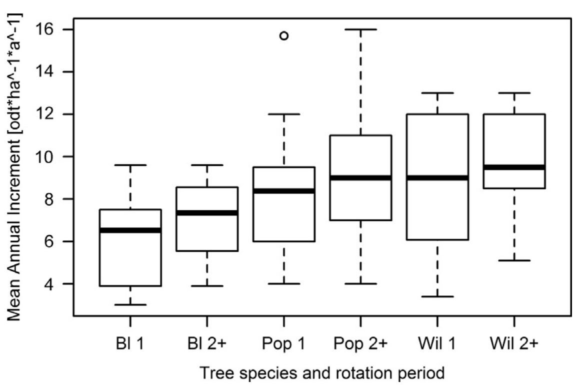

Fig. 6. MAI of black locust (Bl) (n=4), poplar (Pop) (n=13) and willow (Wil) (n=15). Index “1” represents the first rotation. Index “2+“ represents the second and further rotations.

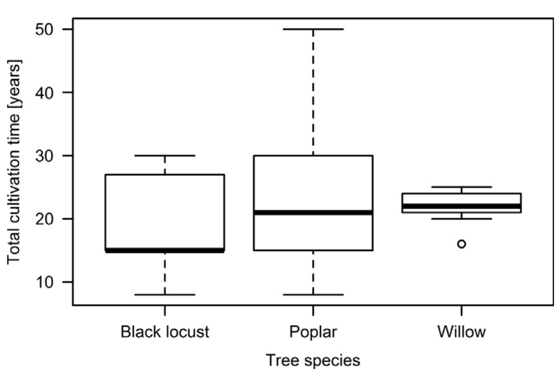

Fig. 7. Total cultivation time of three established SRC tree species in years (n=36).

In general, the total cultivation time depends on the favored end product and rotation length. However, with longer rotation lengths, trees' resprouts are more vital [77]. If the yield level is tolerable, a longer cultivation time can be economically interesting, because the cultivation costs decrease in proportion to the lifetime of an investment. Rosenqvist and Dawson [26], Avohou et al. [36] and Londo et al. [37] stated that the total cultivation time is a very important factor for the economic viability of SRC. In their evaluation, [26] estimated the necessary minimum cultivation time to reach a positive Net Present Value at 16 years.

3.3.4. Planting density

Since planting density directly affects the total cultivation costs of SRC, realistic and appropriate planting densities are recommended. The planting density of the three established SRC tree species varied widely (Fig. 8). Planting densities for black locust

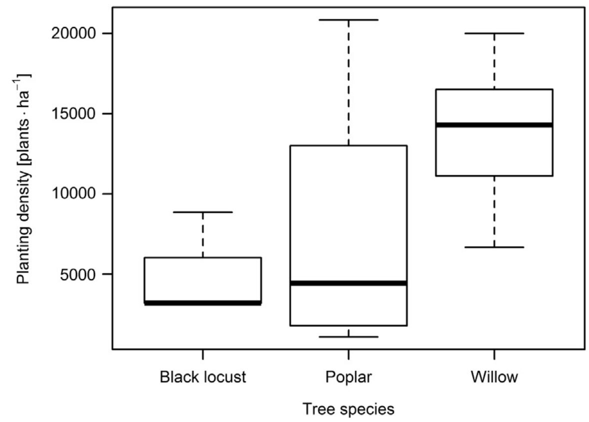

Fig. 8. Planting density [Plants ha^{-1}] of three established SRC tree species (n=26). Willow is the SRC tree species which is cultivated with the highest planting densities, whereas planting densities of poplar are on average much lower. A wider range of assumed planting densities was found for poplar.

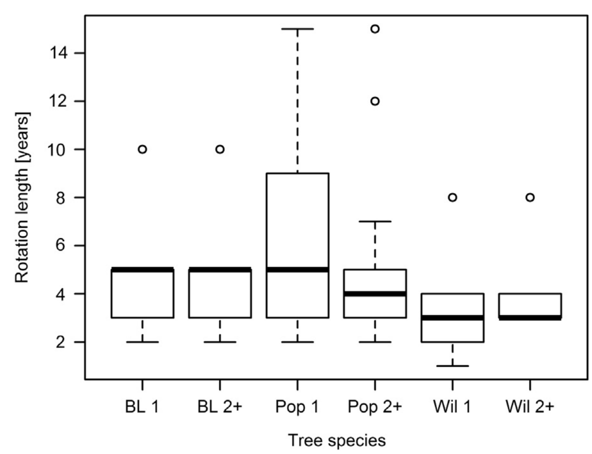

Fig. 9. The rotation lengths [years] of three SRC tree species black locust (Bl), poplar (Pop) and willow (Wil). The additional index “1” represents the first rotation. The additional index “2+“ represents the second and further rotations.

ranged from 3200 to 8860 plants per hectare, with the lowest of all medians at 3200 plants per hectare. Poplar was the tree species with the highest variance in planting density – from 1100 to 20,833 per ha, with a median of 4445 plants per hectare. Willow planting density ranged from 6666 to 20,000, with a median of 14,300 plants per hectare. Hence, the difference in planting density used for willow cultivation was statistically significant – 3.2 times higher than the planting densities of poplar and 4.5 times higher than those assumed for black locust. This must be considered in future calculations. The large variance in the planting densities of poplar may be explained through the wide range of rotation lengths, as the longer the rotation length, the fewer plants per hectare are necessary. On the one hand, high densities result in relatively higher yields per hectare – especially in the first rotation cycle – and faster canopy closure, along with decreased need for weed control [55]. On the other hand, higher planting densities mean higher cultivation costs. Buchholz and Volk [13] conclude: “[…] increased planting density does reduce the overall profitability of the crop over multiple rotations significantly […]. Increasing planting density to raise yield might therefore not result in an improved profitability of the crops.”

3.3.5. Rotation length

The rotation length is the period between cultivation and first harvest, or alternatively the period between one harvest and the

following harvest. It affects the timing of economic benefits delivered by harvested biomass. The rotation lengths of black locust and willow are strikingly similar, whereas the rotation length of poplar deviates (Fig. 9). A Nemenyi–Damico–Wolfe–Dunn test – a post-hoc test which provides a pairwise comparison if the collected data does not follow a normal distribution – showed that poplar had a significantly higher range in rotation length than the other SRC species. The length of the first rotation ranged from two to 15 years, with a median length of five years. Interestingly, in the second rotation, with the exception of two outliers, all of the data was within a much smaller range – between two and seven years, with a median of four years

The differences in length between the first and second rotations in poplar can be explained by the production of round wood. As stated in Section 3.3.3, poplar in fact is an SRC tree species which is also suitable for round wood production. In all studies in our sample where round wood was mentioned, the trees were harvested after the first rotation, stumps were extracted and the land was replanted. Thus, the second rotation of poplar (Pop2) in our database contains only data for wood chips.

The rotation length is an economically interesting variable: The optimal yield increment of SRC poplar, depending on the site conditions, is about ten years [78]. Increasing the rotation length from three to seven years, for instance, leads to both higher yields and better wood quality, due to an increase in wood content relative to bark content. However, there are economic disadvantages, due to delayed cash flows and the necessity of using a more expensive harvesting technique. Burger et al. [61] states that manual harvesting of ten year-old poplars is economically competitive and ecologically preferable to fully mechanized harvesting techniques. In five year old stands, however, manual harvesting is the most expensive harvesting technique, due to the smaller amount of biomass per shoot. Concerning the rotation length, the following conclusion was drawn by [13]: "As long as stem diameters do not exceed the size that can be managed by this harvesting system, longer rotations are more profitable than shorter rotations. The reduction of harvest costs outweigh the negative economic effects caused by delaying the start of positive cash flow due to a longer rotation."

3.3.6. *Interest rate*

The interest rate which is used to discount or prorate cash flows in order to compare values represents the value of invested money itself – the capital costs – and the additional risk premium [59]. For this review, two types of interest rates which are typically used in forestry and agriculture were relevant – (i) the nominal interest rate, which is the payable percentage interest of an investment, (ii) and the real interest rate, which is the nominal interest rate minus inflation.

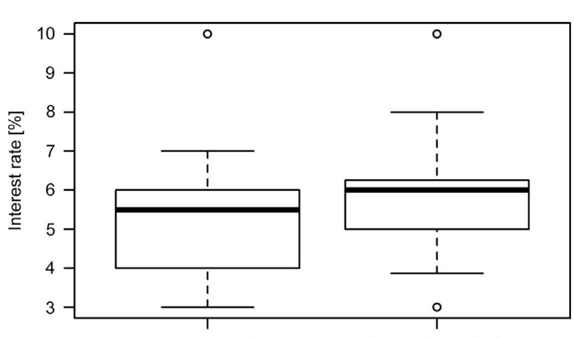

Fig. 10. Interest rates applied in economic calculations of SRC (n=33). If a sensitivity analysis was conducted, the interest rates applied are given in the right Box plot (n=41).

The interest rates used for economic calculation varied from three to seven percent with an extreme value of ten percent, and a median rate of 5.5%. The interest rates used for sensitivity analysis ranged from three to eight percent, with an extreme value of 10% (Fig. 10). The median interest rate among those used in the studies analyzed of 5.5% seems appropriate for agricultural investments [46]. In forestry, expected real interest rates are normally lower 1.5%, according to [79] or from 2 to 6% according to [80]. The application of interest rates appropriate for agricultural investments is reasonable, however, since SRC has to compete with alternative agricultural crops for land.

4. Implications for future dealings with the economics of SRC

As shown in our review, the calculation of profitability for SRC is not trivial. First of all, there is a need for a precise nomenclature for woody biomass production from short rotation coppice. Four different terms were found in the literature – *Short Rotation Forestry, Short Rotation Coppice, Short Rotation Woody Crops* and *Short Rotation Intensive Culture* – all of them basically describing the same process. Therefore a concise definition of the terminology which includes the rotation length as well as rotation length-specific properties (for example, plant density) is recommended.

Due to the long life span of SRC, static methods are not appropriate for calculation of profitability. Dynamic approaches are more appropriate, as they consider the timing of future cash flows and are easy to apply. However, they do have drawbacks such as the difficulty of choosing an appropriate interest rate, and the neglect of uncertainty of future cash flows. The use of different terms for *Annuity – Equivalent Annual Value, Annualized Gross Margin* and *Average Discounted Annual Gross Margin* – in the studies may also cause confusion, and should be standardized. To date, methods of capital budgeting which take into account uncertainty are rarely applied in economic evaluations of SRC. As the timing and amount of cash flows are highly uncertain, due to the long life span of an investment in SRC, approaches which additionally take heed of uncertainty of future cash flows should be applied.

Four different types of *process chains* in SRC operations were distinguished, which contained different working steps and thus differing costs. Each working step consisted of further sub-working steps with the potential for differences among them as well, and there were several ways to perform many working steps. For instance, weeding was carried out both mechanically and chemically. The most important cost units, which have to be chosen carefully due to their high impact on overall costs, are land rent, harvesting and chipping, establishment, and transport. Costs for land preparation and planting must be included in economic calculations of SRC, as they are basis for growth. Costs for weed control should be included until plants reach the stage where they are higher than competing vegetation. However, as these costs are generally relatively insignificant in proportion to the other costs, large investments of time researching appropriate estimations are probably not justified. Instead, average figures based on national-level studies of fertilizer requirements for SRC that consider local or regional soil conditions are no doubt sufficient. In fully mechanized harvesting systems, chipping is accomplished during the harvest, skidding of stems from the harvest site to a second chipping location requires an additional step and therefore, additional costs for handling and chipping must be considered. Costs for loading were stated in only 8 of 37 studies, although biomass must be loaded and unloaded in every process chain with the exception of "cradle to stand", and should therefore be considered in further studies. Only 14 studies considered costs for closing of the plantation. As closing of the

plantation, e.g. stump removal, is costly and necessary if the land is to be converted to agricultural use after the final harvest of SRC, we recommend calculating two scenarios if the subsequent land use is not yet clear – one with and one without costs for closing the plantation. To deliver comprehendible and comparable calculations we recommend precisely describing the underlying process chain and all of the working steps to be performed, including a clearly arranged overview of underlying costs and revenues. This was done in only a few of the studies we analyzed.

In our analysis of the underlying assumptions, we found that tree species-specific differences occurred in planting density – which was assumed to be 3.2 times higher for willow than for poplar, and 4.5 times higher than for black locust. Poplar was found to be the species with the longest rotation length. No statistically significant differences were found in the total cultivation time, biomass prices, biomass yield or interest rate of different species. The revenues from an SRC are *prices* per unit of biomass multiplied by the *amount of biomass*. Both were found to be the most important factors influencing the profitability. The *yield* of SRC for energetic use was given either as total increment per rotation in oven dry tons per hectare [odt ha^{-1}] or as mean annual increment (MAI) [odt ha^{-1} a^{-1}], both of which are suitable. The water content should be indicated if greater than zero. A suitable yield measurement unit for round wood is cubic meters. In that case, water content and density by volume should be given, to make yields comparable to the measurement units of biomass for energetic use.

Bearing in mind the great influence of biomass yield on profitability, (e.g. [23,47]) we suggest calculating highly accurate site-specific biomass yields to facilitate a precise calculation of the profitability of an SRC. Additionally, the yield trend over lifetime should be included (e.g. the increase from first to second rotation).

Both [21,33] criticized the fact that there is too little reliable data on biomass yield under different site conditions. Thus a standardized, transnational arrangement for biomass testing field trials is called for to increase the availability of comparable yield datasets. Furthermore, there is need for a comparison between biomass yields from field trials and those from existing stands managed by farmers.

Large variance in *prices* – even between studies which covered the same time period – and increasing prices over time were found in the studies examined. Moreover, the measurement units to which the prices referred varied, making comparisons of biomass prices difficult. To allow easy comparison of prices, either the reference system of biomass prices for energetic use should be the energy content of the biomass itself, or prices should be given for oven-dry tons. The prices of SRC round wood for material use should be indicated in cubic meters, with the water content specified. Due to the very strong influence of price on profitability, we advise realistic determination of current prices. Additionally, we recommend analysis of past trends and careful definition of future price assumptions, due to the long lifespan of a SRC as well as the uncertainty of future prices. The *interest rate* plays an important and multifunctional role. It represents the value of the money, capital costs and a certain risk premium. Therefore, we recommend the use of an interest rate which includes the value of the land for other uses (i.e. site quality), and which has also been adjusted to take into account the risk due to the uncertainty in future costs and revenues from SRC. Furthermore, it should be indicated if the nominal or the real interest rate has been applied, since they differ significantly. Because SRC is still in its nascency, [72] indicated a high optimization potential and therewith a great potential for increases in the profitability of SRC in the future. Specifically, [72] mentioned the following factors as the ones with the greatest potential for improvement: increasing yield development, improved harvest equipment, rotation optimization, optimized establishment and maintenance. To give quantitative support for likely future trends, and therewith, to increase the accuracy of economic evaluations, cost and yield development over time should be analyzed to a greater extent.

5. Conclusion

To improve economic calculations of SRC we examined 37 studies on economic evaluation of SRC, identified appropriate economic evaluation methods and summarized and discussed the underlying assumptions to provide a basis for future studies. Due to the long lifespan of an SRC, static methods of capital budgeting are not appropriate to evaluate the profitability of SRC. Dynamic methods are suitable if the underlying assumptions are certain – in ex post facto assessments – if not, methods appropriate for uncertain expectations should be applied. The choice of underlying assumptions, particularly the process chain, biomass yield and biomass price, should be made carefully, and clearly stated, as they directly influence both the costs and the benefits. We found evidence that yield level increased by a median of 12.5% from the first to subsequent rotations, and therefore, the development of yield level should be taken into account, by applying regional yield functions over the lifetime of the plantation. Increasing wood chip prices over time and prices for wood chips that are 2.6 times higher than those for non-chipped biomass ought to be considered. We pointed out tree species-specific assumptions, where they occurred. The median planting density of willow of 14,300 plants per hectare was 4.5 times higher than the median planting density of black locust and 3.2 times higher than the planting density of poplar. This can directly affect the establishment costs and therefore must be considered. We also gave suggestions for an appropriate choice of the units used for costs and prices. Additionally, a range of underlying process chains and assumptions was discovered. Even though, it was not possible to identify one single appropriate value per assumption due to different natural conditions and objectives of SRC management, we provided an essential basis for further calculations and underlined the importance of the critical choice of underlying assumptions. Suggestions for ease of traceability and comparability of calculations were also given.

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